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REPRODUCIBLE MUSCLE PERFORMANCE DURING CONSTANT WORK RATE DYNAMIC LEG EXERCISE

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During constant intensity treadmill or cycle exercise, progressive muscle fatigue is not readily quantified and endurance time is poorly reproducible. However, integration of dynamic knee extension (DKE) exercise with serial measurement of maximal voluntary contraction (MVC) force of knee extensor muscles permits close tracking of leg fatigue. We studied reproducibility of 4 performance indices: MVC force of rested muscle (MVCrest), rate of MVC force fall, time to exhaustion, and percentage of MVCrest (%MVCrest) at exhaustion in 11 healthy women (22 + 1 yr) during identical constant work rate 1-leg DKE (1 Hz) on 2 separate days. Means +/- SD, correlation (r) and standard estimate error (S.E.E.) between days were, respectively: a. MVCrest (N), 524 +/- 99 vs 517 +/- 111, 0.91, 43.0; b. MVC force fall (N min-1), -10.77 +/- 9.3 vs -11.79 +/- 12.1, 0.94, 3.6; c. Time to exhaustion (min), 22.6 +/- 12 vs 23.9 +/- 14, 0.98, 2.7; and d. %MVCrest at exhaustion, 65 +/- 13 vs 62 +/- 14, 0.85, 7.8. There were no statistically significant differences between the two test days for any of the performance measures. Low variability of each index should enhance the ability to define the effects of a variety of interventions on voluntary muscle function during constant work rate dynamic leg exercise.

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REPRODUCIBLE MUSCLE PERFORMANCE DURING CONSTANT WORK RATE DYNAMIC LEG EXERCISE

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BACKGROUND

The Thermal and Mountain Medicine Division (TMMD) of the U.S. Army Research Institute of Environmental Medicine in collaboration with the Department of Health Sciences at Sargent College of Health and Rehabilitation Sciences at Boston University have designed, developed, validated, and used a knee extension device for the quantification of progressive muscle fatigue during dynamic leg exercise in humans. A prominent feature of this device is the ability to measure force generating capacity, i.e., muscle fatigue, of the knee-extensor muscles during brief pauses in dynamic leg exercise. Previously we determined that this device provided powerful resolution in detection of changes in force generating capacity. Stepwise accelerations in muscle fatigability were discernable with small increments in exercise intensity and elapsed exercise time. Validity of leg extension exercise for the study of muscle fatigue was established by comparing the relationship of work rate and oxygen consumption during dynamic knee extension exercise to that during conventional ergometry.

In the summer of 1996, an opportunity arose for the TMMD to collaborate with research groups from Boston University, the University of Colorado Health Sciences Center, Denver, CO, and the Palo Alto Veterans Administration Medical Center, Palo Alto, CA to study muscle fatigue in women at sea level and during acclimatization to high altitude. The central, overall hypothesis of that collaborative effort was cyclical variations in ovarian hormone levels throughout the menstrual cycle would alter acclimatization to high altitude. During the conduct of that study, the knee extension device was used repeatedly at sea level and altitude to assess exercise performance and muscle fatigue within and between menstrual cycle phases. This technical report presents an evaluation of test-retest reproducibility of four exercise performance indexes associated with the knee extension device during identical bouts of submaximal constant work rate exercise to exhaustion on two separate days at sea level.

ACKNOWLEDGMENTS

The muscle fatigue studies were partly supported by a Defense Women's Health Research Program (DWHRP) grant titled *"Effect of Menstrual Cycle Phase on Muscle Fatigue and Physical Performance During Altitude Acclimatization"* (#DI950050) and were performed concomitantly during the first year of a three-year project funded by a separate DWHRP grant titled *"Women at Altitude: Effects of Menstrual Cycle Phase on High-Altitude Acclimatization"* (DAMD 17-94-BAA). All work was completed under a Department of Defense contract (DAMD-17-95-C-5110, NIH 14985).

Blood analyses for ovarian steroid hormone concentrations were supported by the General Clinical Research Center of the University of Colorado Health Sciences Center, with funding provided by a Public Health Service Research Grant (5-01-RR00051) from the Division of Research Resources. The authors gratefully acknowledge the technical assistance of Teddi Wiest-Kent of the General Clinical Research Center Laboratory, and Margaret E. Weirman, M.D., for her generous consultation on the interpretation of ovarian steroid hormone concentrations in our volunteers. We also thank William Lasley, Ph.D., and Heather Todd at the University of California, Davis, for assays of urinary estrogen and progesterone metabolites, as well as Quidel, Inc., San Diego, CA, and Diagnostic Marketing Corporation, Englewood, CO, for ovulation predictor and pregnancy test kits.

The authors also wish to thank Jacinda Mawson for recruitment of most of the volunteers. We are most grateful, however, to each of the volunteers who had to endure an incredibly arduous and time-consuming study.

EXECUTIVE SUMMARY

Conventional ergometric modes such as stationary bicycling or treadmill exercise do not readily lend themselves to periodic measurement of maximal voluntary contraction (MVC) force, an index of muscle fatigue. Therefore, the gradually increasing muscle fatigue during maintenance of a required work rate has rarely been systematically studied. To quantitate muscle fatigue during dynamic submaximal leg exercise, an exercise device was developed that permits virtually a complete overlap between the specific muscles used to produce and measure fatigue. Unique features of the exercise device allow the ability to define in detail the effects of four performance measures of voluntary muscle function during each bout of constant work rate exercise ----strength (i.e., MVC force of rested muscle (MVC_{rest})), rate of MVC force fall during exercise, endurance time to exhaustion, and $\%MVC_{rest}$ remaining at exhaustion. To evaluate the test-retest reproducibility of these four performance indexes, eleven women (22±1 yr; mean±SE) performed identical constant work rate (22±2 watts) exercise to exhaustion on two separate days. Means ± SD, correlation (r) and standard estimate error (S.E.E.) between days were:

PERFORMANCE INDEX:	DAY 1	DAY 2	r	S.E.E.
Strength or MVC_{rest} (Newtons)	524 ± 99	517 ± 111	0.91	43.0
MVC force fall ($N \cdot min^{-1}$)	-10.77 ± 9.3	-11.79 ± 12.1	0.94	3.6
Time to exhaustion (min)	22.6 ± 12	23.9 ± 14	0.98	2.7
$\%MVC_{rest}$ at exhaustion	65 ± 13	62 ± 14	0.85	7.8

It was concluded that low variability of each index should enhance the ability to define the effects of a variety of interventions on voluntary muscle function during constant work rate dynamic leg exercise.

INTRODUCTION

Conventional ergometric modes such as stationary cycling or treadmill exercise are not conducive to determine the gradually increasing muscle fatigue inherent during maintenance of a required work rate. As a result, progressive muscle fatigue is typically unobservable, unquantifiable, and not systematically studied during conventional ergometry. Thus, the effects of a variety of environmental, nutritional, or pharmacological interventions on voluntary muscle function during dynamic exercise are not well understood.

Our approach to studying muscle fatigue has been to use an exercise model that integrates measurement of force generating capacity during ongoing dynamic knee extension exercise limited to the quadriceps femoris muscles of one or two legs (1,2,3,7). Force generating capacity is characterized by maximal voluntary contractions (MVCs) obtained prior to, periodically during, and at the end of dynamic knee extension exercise. Previous studies have indicated that such an approach is valid for detecting differences in muscle fatigue rates with only small increments in exercise intensity and elapsed exercise time at sea level and altitude (1,2,3,7).

We evaluated the test-retest reproducibility of four performance indexes associated with the exercise model during identical bouts of submaximal constant work rate exercise to exhaustion on two separate days at sea level. The four performance indexes were: MVC force of rested muscle, rate of MVC force fall, endurance time to exhaustion, and percentage of MVC force remaining at exhaustion.

METHODS

SUBJECTS

Eleven healthy, highly motivated women gave informed written consent and served as subjects. The mean ($\pm$ SE) age, height, and weight of the subjects were 22 $\pm$ 1 yr; 168 $\pm$ 1 cm; and 64 $\pm$ 1 kg, respectively. All had normal and regular menstrual cycles. As a group they were physically active, but not endurance-trained (conventional bicycle ergometer maximal oxygen consumption averaged 44.2 $\pm$ 2 $ml \cdot kg^{-1} \cdot min^{-1}$).

TESTING LOCATION

All preliminary and definitive knee extension tests were performed at the Geriatric Research Education and Clinical Center of the Palo Alto Veterans Administration Medical Center, Palo Alto, CA (altitude: 30 m). Ambient temperature was comfortably maintained (range: 20° to 23° C).

GENERAL EXPERIMENTAL DESIGN AND PROCEDURES

Menstrual Cycle Phase Assessment and Hormone Measurements

Each subject, upon admission to the study, provided a menstrual cycle diary dating back 3 months prior to initial sea-level measurements noting the date and duration of menses. This diary was continued throughout the study and expanded to include the date of the luteinizing hormone (LH) surge. Based upon menstrual history of cycle length, each subject began testing for her LH surge using an ovulation predictor kit (OvuQuick, Becton-Dickson, Rutherford, NJ) at least 4 days prior to the estimated time of her LH surge. Blood for analyses of ovarian steroid hormones was obtained by venipuncture on days 3 and 10 of both the follicular and luteal phases to confirm menstrual phase. All samples were analyzed after completion of the studies.

Exercise Testing Overview

Subjects underwent an average of four preliminary knee extension exercise testing sessions prior to two definitive test sessions. This was done to ensure familiarization with all equipment, personnel, and procedures and to learn to execute dynamic knee extension exclusively with the quadriceps femoris muscles of one leg (1). Preliminary sessions consisted of practicing repeated submaximal static and/or dynamic contractions interspersed with periodic maximal contractions. To allow for muscle recovery for each subject, there were at least three days separating the: 1. last preliminary session from the first definitive test, and 2. two definitive tests.

Based upon menstrual cycle history (and later confirmed by serum hormone levels), definitive tests were conducted on days 1, 5, and/or 9 following either the onset of menses (day 0, follicular phase) or detection of the LH surge (day 0, luteal phase). Eight subjects were studied during their luteal phase and three subjects were studied during their follicular phase. A previous report indicated that exercise performance did not vary significantly ($P > 0.05$) between menstrual cycle phases or among days within each phase (4).

Exercise Device and Procedure for Studying Quadriceps Femoris Muscle Fatigue During Dynamic Contraction Exercise

The specially designed device for performing 1-leg (right leg) dynamic knee extension exercise interspersed with maximal static 1-leg knee extension contractions has been described in detail (1,2). Briefly, it consists of a platform on which the subject sits, an attached minimal-friction weight-pulley system with an ankle harness, transducers for measurement of force and ankle displacement during dynamic knee extension and separate force transducers for measurement of force of static knee extension maximal voluntary contractions (MVCs). In order to precisely control work rate, two vertical columns of 14 light emitting diodes (LEDs) are placed in front of the subject. The right LED column is wired in series to the position transducer (Celesco Transducer Products Inc., Canoga Park, CA, Model PT101-0100-111-1110) such that the number of LEDs lighted is proportional to ankle displacement during knee extension. The left LED column is connected to a synthesizer/function generator which automatically and sequentially lights from one (at the 90° knee angle starting position) to 14 (corresponding to ankle displacement on reaching 150° of knee extension) to one (return to 90° starting position) at a pre-determined knee extension rate of 1 Hz.

To maintain correct distance and rate of dynamic knee extension, the subject continuously matched the column of LEDs controlled by leg movement with that controlled by the synthesizer/function generator. The LED units simplify subject and investigator monitoring of adherence to the required work rate. Because the knee extension movement encompasses 60° and there are 13 intervals between LEDs, the maximum allowable difference between the desired and actual knee extension angle is 4.62°. Muscle exhaustion is defined as a mismatch of only one LED between the right and left LED columns for 3 consecutive knee extensions; meaning that exhaustion is associated with an inability to complete the last 5° of knee extension contraction--from 145° to 150°---

at the required contraction rate. Voltages proportional to force and ankle displacement were continuously recorded. Work rate (watts) was determined by multiplying mean force developed per contraction, distance of ankle movement during knee extension from 90° to 150° and rate of knee extension (1 Hz).

To measure the decline in force generating capacity and rate of muscle fatigue, the exercise device allowed performance of MVCs of the knee extensor muscles during brief ($\leq$ 5 sec) pauses in dynamic knee extension. This procedure involved rapid disconnection of the ankle harness from the weight-pulley system, connection to a force transducer dedicated to measurement of MVC force, actual measurement of MVC force, and reconnection to the weight-pulley system.

<u>Determination of MVC Force</u>. On each day of definitive testing, the subjects performed three or more pre-exercise knee extensor MVCs with the right leg. Each MVC was followed by at least 1 min of rest. MVC force ("strength" or rested MVC force) of the right leg was then measured immediately prior to, at the end of every 2 min during and immediately following dynamic knee extension. Each MVC lasted 2 to 3 sec. A knee angle of 90^0 was used for all MVCs.

<u>Submaximal Constant Work Rate Knee Extension Exercise</u>. For each subject, 1-leg dynamic knee extension at a frequency of 1 Hz was performed to exhaustion at the same constant work rate (22 ± 2 watts) during the two definitive exercise tests. The time course of fatigue was determined from MVC force measurements during pauses of $\leq$ 5 sec at the end of every two min of exercise and immediately post-exercise. For the second definitive test, neither the subjects not the investigators were aware of any results of the first definitive test. The four performance indexes associated with the dynamic knee extension exercise model are depicted in **FIGURE 1.**

<u>Respiratory Gas Exchange</u>. Respiratory gas exchange (Sensormedics Metabolic Cart, model 2900) were continuously monitored for both definitive exercise sessions.

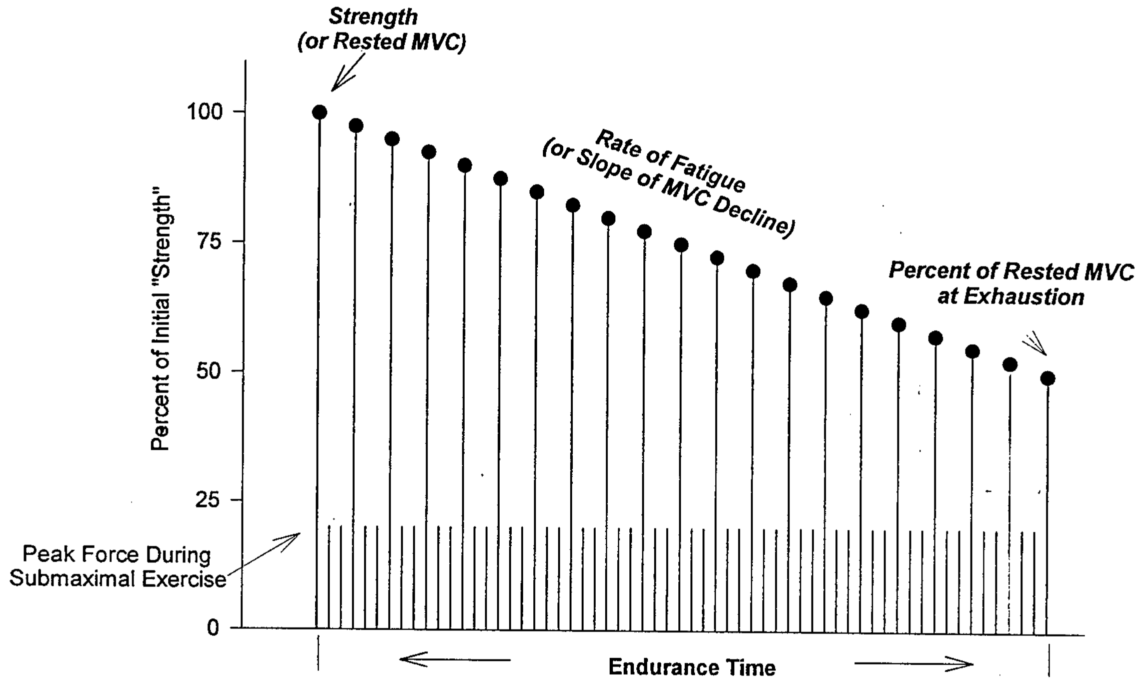

Figure 1: Schematic of dynamic knee extension model. "*Strength*" or MVC of rested muscle is the highest maximal voluntary static contraction (MVC) force obtained prior to the start of dynamic exercise. Peak force during each dynamic knee extension is the product of the amount of weight lifted and the speed with which the weight is displaced. A MVC also is performed at the end of every 2 min. "*Rate of Fatigue*" is defined as the rate of decline of MVC force resulting from dynamic knee extension exercise. "*Exhaustion*" occurs when an individual is unable for three consecutive contractions to maintain the rate of knee extension and/or the distance of ankle movement. In the figure, the peak force during each submaximal contraction equals 20% of MVC force of rested muscle, a MVC is performed every two min of dynamic knee extension, and, at exhaustion, the percent MVC force equals 50% that of rested muscle (1,7).

RESULTS

There were no statistically significant differences between the two definitive test days for submaximal work rate (expressed as watts or percentage of MVC_{rest}) or for steady-state oxygen consumption.

TABLE 1. Submaximal Work Rate and Oxygen Consumption During Dynamic Knee Extension Exercise.

	Test Day 1	Test Day 2
Submaximal Work Rate (watts)	**22 ± 2**	**21 ± 2**
Submaximal Work Rate (%MVC_{rest})	**21 ± 2**	**20 ± 2**
Oxygen Consumption (ml·min^{-1})	**698 ± 27**	**651 ± 31**

For **Figures 2 to 5**, the test day 1 and test day 2 values for each of the 11 subjects are plotted in relation to a line of identity. For test days one and two: a. *Rested MVC force* was 524 ± 99 N (mean ± SD) and 517 ± 111 N; b. *Endurance time to exhaustion* was 22.6 ± 12 min and 23.9 ± 14 min; c. *Fatigue rate* (slope of MVC force decline per min of exercise) was -10.77 ± 9.3 N·min^{-1} and -11.79 ± 12.0 N·min^{-1}; and d. *Percentage of rested MVC force remaining at exhaustion* was 65 ± 13% and 62 ± 14%. There were no statistically significant differences between the two test days for any of the performance measures.

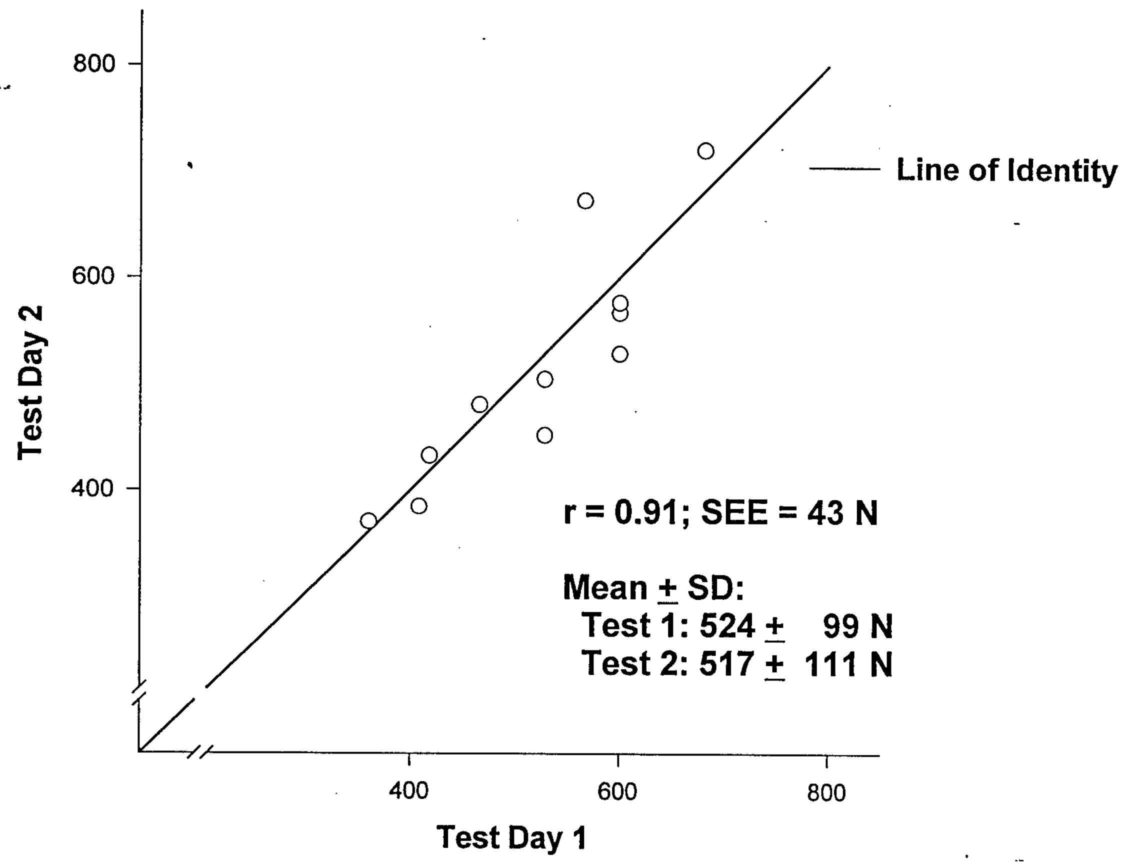

Figure 2: Test-retest for rested MVC force

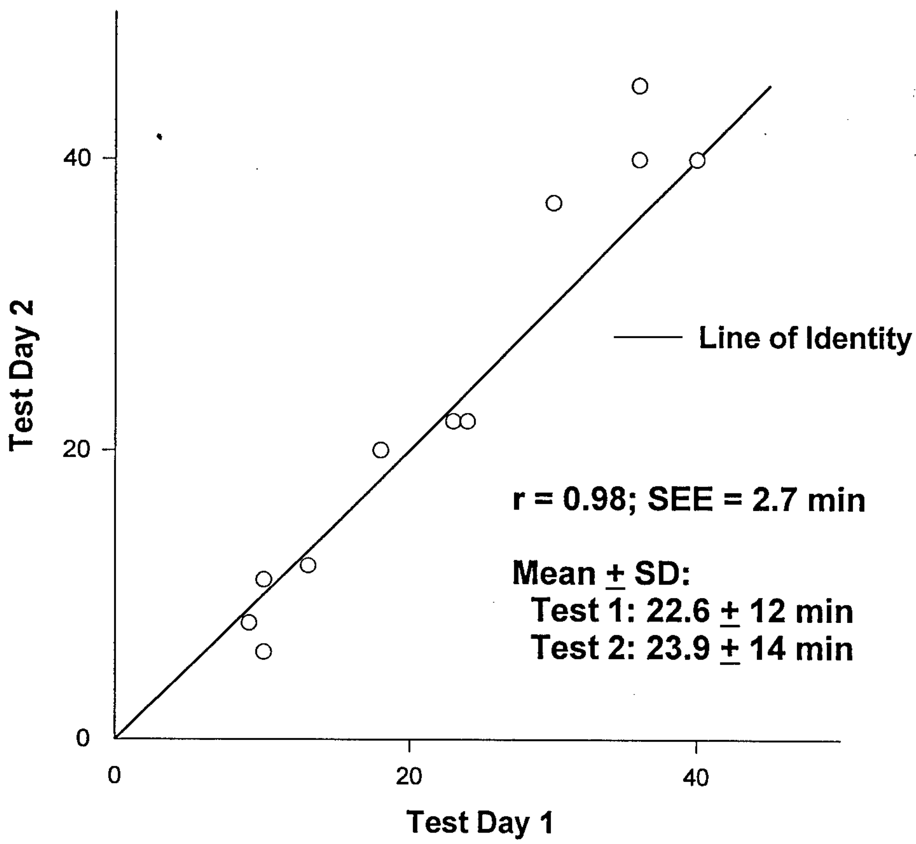

Figure 3: Test-retest for endurance time to exhaustion

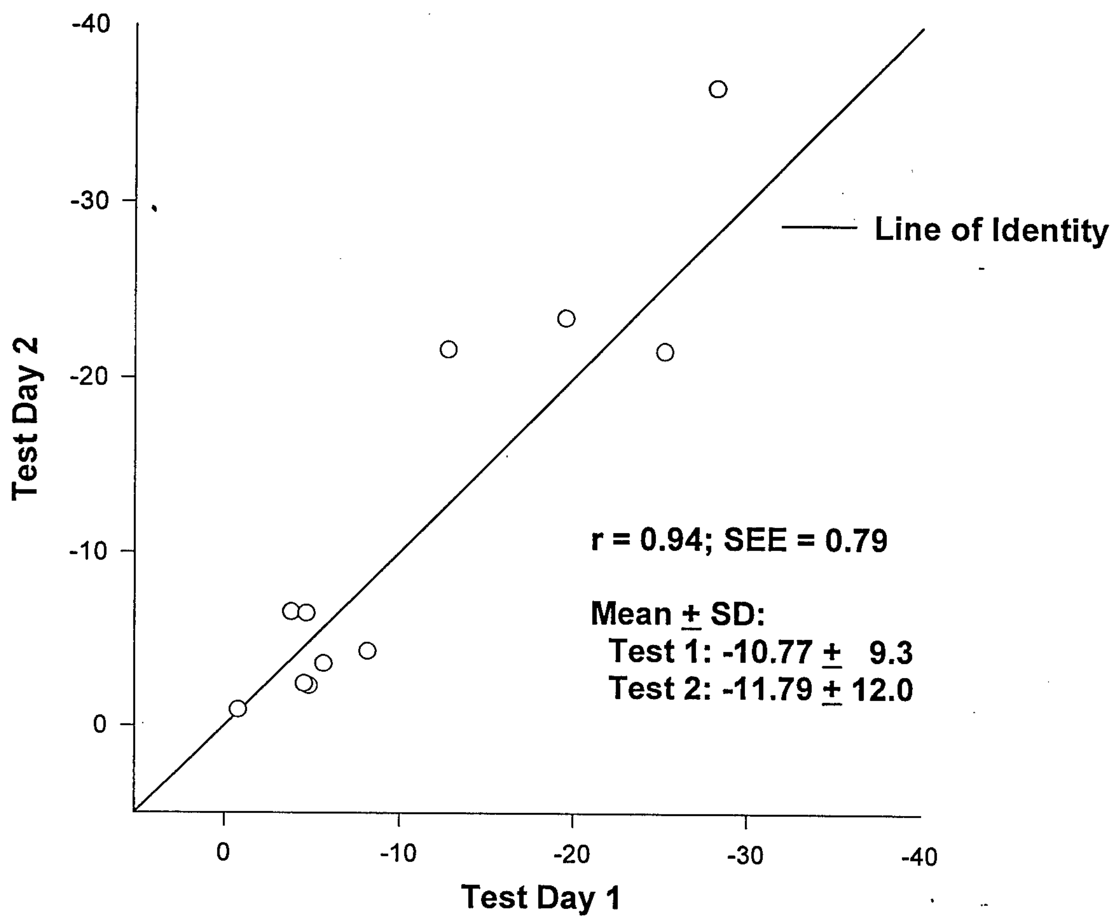

Figure 4: Test-retest for fatigue rate (MVC decline·min^{-1})

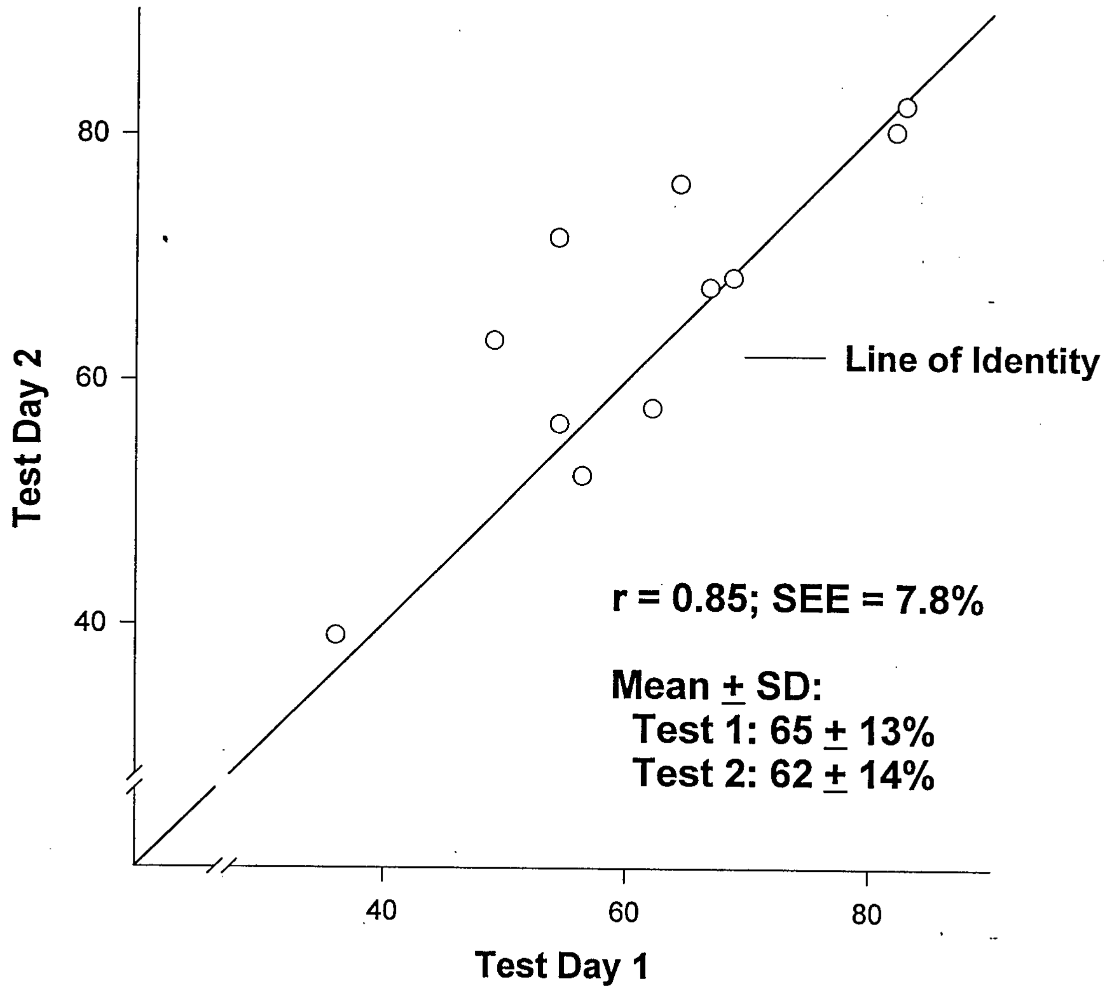

Figure 5: Test-retest for percentage MVC force at exhaustion

DISCUSSION

Because conventional ergometric modes such as stationary cycling or treadmill exercise do not readily lend themselves to periodic measurement of muscle force generating capacity, gradually increasing fatigue during maintenance of a required work rate has rarely been systematically studied (7). By integrating measurement of knee extensor MVC with ongoing dynamic knee extension, the present fatigue model provides the ability to quantitate the progressive decline in force generating capacity during constant work rate dynamic exercise (1,3,7).

Unique features of the knee extension exercise model enhance the ability to define in detail the effects of a given intervention on four performance measures of voluntary muscle function during a single bout of constant work rate exercise --- MVC force of rested muscle, rate of MVC force fall, endurance time to exhaustion, and percentage of MVC force at exhaustion --- which can either increase, decrease or not change. This theoretically permits 4^3 or 64 different specific combinations of effects of an acute or chronic intervention on knee extensor muscle performance. In contrast, for conventional constant work rate bicycle or treadmill exercise, endurance time to exhaustion often serves as the only measure of performance, and only three overall effects --- an increase, decrease, or no change --- are observable.

Moreover, each of the four performance measures of the knee extension exercise model has relatively minor intra-individual test-retest variation. Reproducibility of knee extensor MVC force of rested muscle as measured by correlation coefficient (r) or test-retest percentage variation is similar to that reported previously (6,8,9). Also, there is much less within-subject variation in endurance time to exhaustion measured during repeated bouts of dynamic knee extension exercise compared to repeated bouts of bicycle ergometry, even in even in subjects familiar with exhaustive leg exercise such as well-trained long distance cyclists (5). There are no previous reports with which to compare during dynamic contraction exercise either rate of MVC force fall or percentage of MVC force remaining at exhaustion.

Minimization of test-retest variability of knee extension exercise performance measurements improves the resolution for detecting potential changes caused by a given intervention. For example, a power analysis ($n = 15$; αlpha = 0.05; beta = 0.25 (10)) indicated that in order to demonstrate statistical significance, an intervention would have to improve endurance time to exhaustion by more than 17% during conventional cycling (5) but by less than 11% during dynamic knee extension. The biggest benefit of the knee extension exercise model, however, relates to low variability of *each* of four performance indexes that are measured during the conduct of *a single test session.* Having more than performance index measured during the conduct of each test session should enhance the ability to more precisely define the effects of a variety of interventions on voluntary muscle function during constant work rate dynamic leg exercise. Another advantage of the dynamic knee extension model is that the muscle fatigue rate --- calculated from multiple periodic measurements of MVC force from rest to exhaustion --- is unlikely to be markedly affected by, for example, an occasional poorly performed MVC due to a momentary lapse in motivation or concentration, or by a nonrecorded MVC due to technical problems.

The ability to demonstrate multiple effects of an experimental intervention for an entire group of individuals as well as specific individuals within a group is illustrated qualitatively by nine of the 11 women in the current study who were later tested within 24 hours of exposure to an altitude of 4,300 m (4). For each panel in **Figure 6**, the sea level (from test day 2) and altitude scores for the 9 subjects are plotted in relation to a line of identity. In general, at altitude compared to sea level, rested MVC force was enhanced, rate of muscle fatigue accelerated, and endurance time and percentage of rested MVC force at the point of exhaustion were reduced. In addition, within this group of women, individual responses for the sickest woman at altitude (indicated by "*") and the woman whose leg had a "burning pain" during exercise at altitude (indicated by "+") are indicated within each panel of the four performance measures of voluntary muscle function. As shown, both of these women had identical endurance times at sea level; but responded quite differently during altitude exposure. The woman who was the sickest at altitude had less strength, similar endurance and fatigue rate, and attained a lower percentage of rested MVC force at the point of exhaustion at altitude compared to sea level. The women whose active leg had a "burning pain" during submaximal exercise at altitude had similar strength and percentage of rested MVC force at the point of exhaustion, and a much reduced endurance time and fatigue rate at altitude compared to sea level.

In summary, this exercise model permits quantitation of progressive muscle fatigue during ongoing dynamic leg extension exercise. An exercise model having four performance indexes with low test-retest variability and measured during the conduct of a single test session should enhance study of the effects of a variety of interventions on voluntary muscle function during constant work rate dynamic leg exercise.

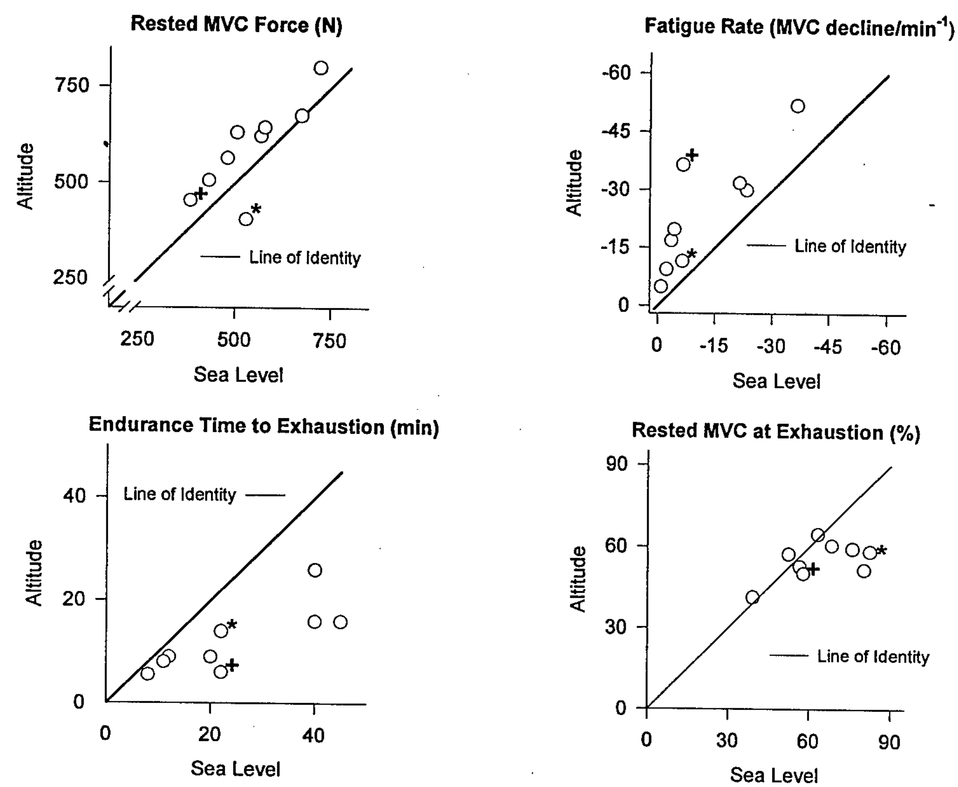

Figure 6: Interaction of muscle strength, fatigue rate, endurance time to exhaustion, and percentage of MVC force recorded at the point of exhaustion during hypobaric hypoxia.

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